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METHOD OF MAKING A TUNABLE LASER SOURCE WITH INTEGRATED OPTICAL AMPLIFIER

Cross-Reference to Related Application

~~This application is a continuation-in-part and claims the benefit of priority of U.S. Provisional Application Serial No. 60/152,072, filed September 2, 1999, U.S. Provisional Application Serial No. 60/152,049, filed September 2, 1999, U.S. Provisional Application Serial No. 60/152,038, filed September 2, 1999, which applications are fully incorporated by reference herein. This application is also a continuation-in-part of U.S. Serial Nos. __________, __________, __________, __________, __________, __________, __________, and __________, filed on the same date as this application and identified as Attorney Docket Nos. 23444-704, 23444-705, 23444-706, 23444-707, 23444-708, 23444-709, 23444-710 and 23444-711, which applications are fully incorporated by reference herein.~~

Field of the Invention

This invention relates generally to laser assemblies, and more particularly to a widely tunable laser assembly with an integrated optical amplifier.

Brief Description of the Related Art:

Thin fibers of optical materials transmit light across a very broad frequency bandwidth and therefore communications data from a light source may be transmitted over such fibers over broad frequency ranges. At any particular frequency, a laser source must have high output power, narrow laser linewidth and good transmission performance through great distances of optical fiber.

In higher bandwidth communications systems, where many frequencies of laser light are transmitted along a fiber, there may be one or several laser sources. While a tunable laser source would be preferred, higher data capacity systems presently use multiple laser sources operating on different frequency channels to cover the wide fiber transmission bandwidth. This is the case since appropriate laser sources are presently

incapable of rapid, electronic frequency tuning without attendant deterioration of other significant figures-of-merit.

For example, at a fixed frequency, sampled grating distributed Bragg reflector (SGDBR) lasers have the high output power, narrow laser linewidth and good transmission performance necessary for an optical data network. While some SGDBR lasers can be rapidly tuned over more than 100 different transmission channels, two problems nevertheless prevent these devices from being employed in fiber optic communication systems. The most significant problem is the significant absorption of the mirror material. The resulting large cavity losses act to make the laser output power insufficient for the requirements of a present-day communications system. A second problem is that the output power and frequency tuning are dependent on each other. This coupling results in inadequate controllability for a present-day communications system.

What is needed, instead, is a device with a combination of sufficiently high output power for a high-bandwidth optical communications network and with frequency tuning controllability substantially independent of output power controllability.

SUMMARY

Accordingly, an object of the present invention is to provide an integrated laser assembly that includes a tunable solid state laser and optical amplifier where all of the elements are fabricated in a common epitaxial layer structure.

Another object of the present invention is to provide an integrated laser assembly that includes a tunable solid state laser and optical amplifier with an output mode conditioned for transmission in an optical fiber.

Another object of the present invention is to provide an integrated laser assembly that includes a tunable laser and optical amplifier reducing optical feedback from the amplifier to the laser.

A further object of the present invention is to provide a tunable, integrated laser assembly where laser frequency control and output power control are substantially independent.

These and other objects of the present invention are achieved in a laser assembly that includes an epitaxial structure formed on a substrate. A tunable laser resonator and a separately controllable optical amplifier are formed in the common epitaxial structure. The amplifier is positioned outside of the laser resonator cavity to receive and adjust an

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output received from the laser, however, at least a portion of the laser and amplifier share a common waveguide.

C1 ~~In different embodiments of the present invention, properties of the common~~ waveguide such as optical properties, or centerline ~~curvature~~ or cross-sectional are non-uniform along or the waveguide centerline or non-uniform across a normal to the ~~centerline.~~

BRIEF DESCRIPTION OF THE FIGURES

Figure 1A is a block diagram of a laser assembly that illustrates different functional elements of a laser assembly.

Figure 1B is a cross-sectional view of one embodiment of a widely tunable laser assembly of the present invention and the integration of materials with differing optical properties by an offset quantum well technique.

C2 ~~Figure 2A is a cross-sectional view one embodiment of an amplifier illustrating~~ several layer structures ~~and the~~ integration of two materials with differing optical ~~properties by a selected area growth technique.~~

C3 ~~Figure 2B is a cross sectional view of the Figure 2 assembly illustrating one~~ embodiment for the integration ~~of~~ materials with differing optical properties by a ~~disordered well technique.~~

C4 ~~Figure 2C is a cross-sectional view one embodiment of an amplifier illustrating one~~ embodiment for the integration ~~of~~ several different band gap materials by a butt joint ~~regrowth technique.~~

Figure 3A is a cross-sectional view of one embodiment of the Figure 1 optical amplifier element where a portion of the waveguide is curved and an interface between an active and a passive section is oblique.

Figure 3B is a cross-sectional view of one embodiment of the Figure 1 optical amplifier element where the amplifier includes a plurality of gain sections.

Figure 3C is a cross-sectional view of one embodiment of the Figure 1 optical amplifier element where the amplifier includes a flared waveguide.

Figure 3D is a cross-sectional view of one embodiment of the Figure 1 optical amplifier element where the amplifier includes a waveguide mode adapter.

DETAILED DESCRIPTION

Figure 1A shows a schematic of an embodiment of the invention. In Figure 1A, laser assembly 100, waveguide 105, amplifier gain section 110, front resonator mirror 120, laser gain section 130, laser phase control section 140, back mirror 150 and electrical contact 160, epitaxial structure 170, laser 180, optical amplifier 190 and output facet 195 are shown.

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~~In Figure 1A, laser assembly 100 comprises an integration of a laser and an optical~~ amplifier, with the optical amplifier located external to the laser cavity. Front resonator mirror 120, laser gain section 130, laser phase control section 140, and back mirror 150 form a SGDBR-type laser 180 in epitaxial structure 170. The front and back mirrors define a laser cavity. Amplifier gain section 105 and a portion of waveguide 105 define ~~optical amplifier 190.~~

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~~As shown in Figure 1A, despite being external to the laser cavity, the optical~~ amplifier shares a common epitaxial structure 170 with the laser. Epitaxial structure 170 is formed on a substrate (not shown) by processes well-known in the art of semiconductor fabrication. By tailoring optical properties (such as band gap) of different portions of the epitaxial structure, both optically active and optically passive sections can be fabricated in a common structure. Examples of optically active sections of the embodiment shown in Figure 1 are gain sections 110 and 130, phase control section 140 and mirrors 110 and 150. An example of an optically passive section is the portion of waveguide 105 proximal ~~to output facet 195~~.

According to the invention, at least a portion of laser 180 and optical amplifier 190 share a common waveguide 105. Different portions of the common waveguide may extend through optically active or passive regions. A common waveguide for the laser and optical amplifier enables the output from the laser to be directly coupled into the amplifier.

In the embodiment of Figure 1A, amplifier 190 is external to the resonant cavity of laser 180 formed by mirrors 120 and 150. Moreover, amplifier gain section 110 is separately controllable from the laser and is adjustable to increase or decrease the light intensity and output power. The SGBDR laser elements may be controlled separately from the amplifier to tune the laser frequency and otherwise control the input to the optical amplifier. By this arrangement of elements, power amplification and tuning functions are substantially uncoupled.

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~~In the embodiment of Figure 1A, optical amplifier 190 has an active section and a~~ passive section. The active section, amplifier gain section 110, is substantially straight. The passive section of waveguide 105 is curved ~~and~~ intersects output facet 195 at an oblique angle. Both waveguide curvature and the oblique intersection with the output facet act to prevent reflections at the output facet from coupling back into the optical ~~amplifier and laser 180.~~

Figure 1B shows a longitudinal cross section of a laser assembly 100 of Figure 1A. In Figure 1B, laser assembly 100, waveguide 105, amplifier gain section 110, front resonator mirror 120, laser gain section 130, laser phase control section 140, back mirror 150 and electrical contact 160, epitaxial structure 170, laser 180, optical amplifier 190, output facet 195, p type semiconductor layer 125, n-type semiconductor layer 115, mirror sampling period 135, offset quantum wells 145 and stop etch layer 155 are shown.

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~~In Figure 1B waveguide 105 is formed between p-type and n-type semiconductor~~ layers 125 and 115, respectively. Mirrors 120 and 150 are formed by sample gratings ~~etched in waveguide 105 with sampling period 105, as is well understood in the art.~~

Figure 1B illustrates the structure resulting from an offset quantum well technique for optically active and passive section formation. According to the offset quantum well technique, the optically active sections have multiple quantum well layers 145 grown in a region offset from waveguide 105. The multiple quantum well layers are separated from the waveguide by a thin stop etch layer 155. Removal of quantum wells, by etching for example, forms optically passive sections.

Figures 2A-2C illustrate cross-sectional structures over a portion of laser assembly 100 (see Figure 1) resulting from different techniques for forming optically active and passive sections and their junctions. Figure 2A illustrates a cross-sectional structure over a portion of laser assembly 100 (see Figure 1) resulting from a selected area regrowth technique. The selected area regrowth technique uses a dielectric mask to selectively control the growth rate and composition over different areas of the epitaxial structure. Thus, the material's bandgap can be shifted in certain sections making the material in that section passive or non-absorbing at desired wavelengths. In Figure 2A, optically passive section 210, optically active section 220, bandgap-shifted quantum wells 230, active section quantum wells 240, and waveguide 105 (see Figure 1A-1B) are shown. In Figure 2A, different portions of waveguide 105 are optically active or passive due to bandgap-shifting of the quantum wells within the waveguide.

Figure 2B illustrates a cross-sectional structure over a portion of laser assembly 100 (see Figure 1) resulting from a selected area disordering technique for forming optically active and passive sections. The selected area disordering technique uses a dielectric cap or ion implantation to introduce vacancies which can be diffused through an active region to disorder the quantum wells by intermixing them. This disordering shifts quantum well bandgaps, creating optically passive waveguide sections.

In Figure 2B, optically passive section 210, optically active section 220, disordered wells 250, active section multiple quantum wells 260, and waveguide 105 (see Figure 1A-1B) are shown. In Figure 2B, different portions of waveguide 105, sections 210 and 220, are optically active or passive due to the organization of the quantum wells within the waveguide material.

Figure 2C illustrates a cross-sectional structure over a portion of laser assembly 100 (see Figure 1) resulting from a butt joint regrowth technique for forming optically active and passive sections. According to the butt joint regrowth technique, the entire waveguide is etched away in optically passive sections and an optically passive waveguide is grown again. The newly grown portion of the waveguide is butted up against the active waveguide. In Figure 2B, optically passive section 210, optically active section 220, active, butt-joint interface 270, passive waveguide section 275, active waveguide section 285 and waveguide 105 (see Figure 1A-1B) are shown. In Figure 2B, active waveguide section 285 and passive waveguide section 275 are separated by a distinct large gradient butt-joint interface 270 as a result of the etch removal process.

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~~Figures 3A-3D are plan views, illustrating different embodiments of optical~~ amplifier 190 (see Figure 1). In Figures 3A-3D ~~optical~~ amplifier 190, waveguide 105, epitaxial structure 170, output ~~facet 195~~, active amplifier section 310 passive amplifier section 320~~, active~~-passive junction 330, curved waveguide portion 340, flared waveguide ~~portions 350 and 355 and waveguide mode adapter 360 are shown.~~

In Figure 3A, optical amplifier 190 has an active amplifier section 310 combined with a passive amplifier section 320, where the passive amplifier section includes curved waveguide portion 340. The curved waveguide portion intersects output facet 195 at an oblique angle. Both the waveguide curvature and oblique intersection significantly reduces the amount of light reflecting from the output facet back into the amplifier and laser. Active-passive junction 330 is preferably oblique to a centerline of waveguide 105 so that any reflections from this interface coupling back into the amplifier and laser will be

reduced. However, alternate embodiments may have active-passive junction 330 substantially normal to a centerline of the waveguide.

Figure 3B shows an alternate embodiment where the amplifier active section has been segmented into a plurality of active sections in order to increase the amplifier output power and reduce a noise figure. In this embodiment shown in Figure 3B, the amplifier active section is segmented into two amplifier active sections 310 that may be independently controllable. Other embodiments have more than two amplifier active sections. This segmenting of the amplifier enables the use of different bias points for the different sections. Having a plurality of amplifier stages allows higher saturated output powers to be reached with better noise performance.

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~~Figure 3C shows an alternate embodiment where a waveguide portion in the amplifier active section is flared, or tapered, to increase the saturated output power. Flared waveguide portion 350 increases the amplifier active volume as compared to the embodiment shown in Figure 3A and decreases the photon density. To accomplish this effectively without introducing significant fiber coupling difficulties it is preferable to use an adiabatic flare, wherein there is no energy transfer across optical modes over the flare to a wider waveguide cross-section. In a preferred embodiment, a second flared-down section 355 to a narrow waveguide cross-section is positioned in the amplifier optically passive section 320 since it is difficult to couple effectively from a wide waveguide into a single mode fiber at output facet 195. In a preferred embodiment, such a flared-down portion is before a curved waveguide portion 340, otherwise, higher order modes will be excited when curving the wide waveguide.. In the embodiment shown in Figure 3C, active-passive junction 330 is angled so that any reflections from this interface coupling back into the amplifier and laser will be reduced.~~

Figure 3D shows another embodiment including a waveguide mode adapter. A waveguide mode adapter is preferred in many embodiments to enlarge the optical mode near output facet 195 so that it is more closely matched to the mode in an optical fiber that, as an element in a communications system, may carry the light away from the output facet. Including a waveguide mode adapter thus reduces the fiber coupling loss and increases the alignment tolerances between laser assembly 100 (see Figure 1) and an optical fiber of another system. An embodiment of a waveguide mode adapter includes a section of passive waveguide wherein the waveguide's cross sectional is varied to expand the waveguide optical mode in an adiabatic manner.

The foregoing description of a preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously, many modifications and variations will be apparent to practitioners skilled in this art. It is intended that the scope of the invention be defined by the following claims and their equivalents.

What is claimed is: